Fermilab

TM-1033
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Measurement of He Leak into the Cold Bore of Superconducting Magnet for Energy Saver

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1. Introduction

In the Doubler vacuum system, a He-accumulation rate must be lower than the value of 1×10^{-3} monolayer/year. This value corresponds to 2.8×10^{-11} Torrℓ/sec He-leak rate for each bending magnet. Such a low He leak can never be detected by a normal He leak detection procedure, because of the He adsorption onto the cold bore surface at 4.7K. And, He-leak measurement must be carried out while the bending magnet is cooled down to a normal operation temperature. Therefore, a build-up method should be applied to this measurement. In principle, this build-up test system, as shown in Fig. 1, consists of three parts and each one is as follows:

1) A build-up chamber including a bending magnet.
2) Pressure measurement devices for He partial and total pressure.
3) A pumping system for roughing.

These parts are connected through valves.

The measurement procedure of this method is as follows:

1) After the pressure of the system reached high-vacuum, valve V_1 is closed off and the bending magnet is cooled down to normal operation temperature for a certain period of time (hours-days). In this period, leaked He (if any) is adsorbed mostly onto the cold surface.
2) After the period of an accumulation, V_2 is closed and V_1 is

opened. Then the bending magnet is warmed slowly up to 20K. At 20K only two kinds of gasses, He and H_2, can be desorbed and other gas species, i.e., CO or H_2O or hydrocarbons, still remain on the cold surface. Therefore, the total pressure in the chamber can be maintained low enough for He partial pressure measurement.

In a calculation of an accumulated He amount, "thermal transpiration effect" must be considered.

This effect takes place in the case where the temperatures of two chambers are not the same and a mean free path is far longer than the size of the chambers. In the case of no net gas flow across the aperture connecting two vacuum chambers, the fluxes from both sides must be equal.

$$\frac{1}{4} n_1 \bar{v}_1 = \frac{1}{4} n_2 \bar{v}_2$$

which leads to a well-known relation

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}$$

This equation, which represents the law of the thermal transpiration effect, must be considered in the calculation of a total He amount from the partial pressure measured in the warm chamber connected to the cold bending magnet bore tube.

2. Principle

An illustration in Fig. 1 shows a simple layout of the cold bore tube and measurement port, the temperature, pressure, mean velocity and molecular density are expressed by T, P, $\bar{\nu}$ and n, respectively. The characters of T_r and T_b stand for room and bore tube temperatures, respectively. The standard value of T_b is supposed to be around 20K.

On equilibrium condition, there is no net gas flow across the aperture, therefore, the fluxes from both sides must be equal.

$$\frac{1}{4}\, n_{T_b} \bar{\nu}_{T_b} \qquad \frac{1}{4}\, n_{T_r} \bar{\nu}_{T_r} \tag{1}$$

where details of notation are listed in Table 1. The pressures in the two chambers are given by

$$P_{T_b} = n_{T_b} k\, T_b \tag{2}$$

$$P_{T_r} = nT_r k\, T_r \quad . \tag{3}$$

The energies of molecules in two chambers are

$$E_{T_b} = \frac{1}{2}\, m_{He}\, \bar{\nu}_{T_b}{}^{2} = \frac{3}{2}\, kT_b \tag{4}$$

$$E_{T_r} = \frac{1}{2}\, m_{He}\, \bar{\nu}_{T_r}{}^{2} = \frac{3}{2}\, kT_r \tag{5}$$

From eq. (1) to (5), the ratio of the pressure in the bore tube to that in the measurement chamber is written as

$$\frac{P_{T_b}}{P_{T_r}} = \left(\frac{T_b}{T_r}\right)^{\frac{1}{2}} \tag{6}$$

The total number of He, Nt, in the cold bore tube can be expressed

$$N_t = \frac{P_{T_b} V_b}{kT_b} = \sqrt{\frac{1}{T_r T_b}}\; P_{T_r}\, \frac{V_b}{k} \tag{7}$$

Considering the surface area, A, of the bore tube and the number of molecules of 1-monolayer He on the unit surface, the He accumulation rate is expressed as,

$$\begin{aligned} M &= \frac{N_t}{mA} \cdot \frac{365 \times 24}{t_{hr}} \\ &= P_{T_r} \cdot \frac{1}{mA} \cdot \sqrt{\frac{1}{T_r T_b}} \cdot \frac{V_b}{k} \cdot \frac{365 \times 24}{t_{hr}} \quad \text{(monolayers/year)} \end{aligned} \tag{8}$$

To obtain P_{T_r} in eq. (8), however, a correction is necessary to the He partial pressure (P_{MA}) measured by a mass analyzer.

Suppose, the mass analyzer is calibrated to B-A gauge and this coefficient is S_{MA-BA}. The B-A gauge represents a nitrogen equivalent pressure and the relative sensitivity of He to N_2 is $S_{N_2-H_2}$.

To obtain the He pressure P_{T_r}, these two coefficients should be multiplied to P_{MA}

$$P_{T_r} = S_{MA-BA}\, S_{N_2-He}\, P_{MA} \tag{9}$$

where S_{N_2-He} is about 4 $\sim$ 5 for an ionization gauge, and the value of S_{MA-BA} depends on the mass analyzer head and also the tuning of electronics of the mass analyzer.

Putting eq. (9) to (8) leads to the following formula for the He accumulation rate

$$M = \frac{P_{MA}\, S_{MA-BA}\, S_{N_2 He}}{t_{hr}} \;\frac{1}{m \cdot A}\; \sqrt{\frac{1}{T_r T_b}} \cdot \frac{V_b}{k}\; (365 \times 24) \tag{10}$$

(monolayers/year)

where, m is 2.6×10^{15} molecules/cm^2 for stainless steel surface, and S_{N_2-He} is 4.8 for a B-A gauge.

P_{MA}, T_b and t_{hr} are obtained in the routine measurement and SMA-BA can be checked in a present set-up, if necessary. (For checking SMA-BA, see Appendix.)

3. Outline of Measurement System and Procedure

A measurement system is shown in Fig. 2. Setting the warm bore through the magnet, two double O-ring elastomer seals are set at the upstream end of the magnet, and the other end of the warm bore is sealed by a metal C-seal. The volume between the double O-ring seal is connected to a thermal insulation vacuum of the magnet through a copper tubing. This double O-ring seal is necessary for preventing the possible He-permeation through an elastomer gasket from atmospheric environment. He molecules, permeating through the outer O-ring is pumped out to the insulation vacuum, and He permeation into the cold bore through the inner elastomer O-ring can be reduced to a quite low level.

Outline of the measurement procedure is as follows:

After a completion of a magnet installation, the cold bore is evacuated through the valves V_1 and V_2 in Fig. 2. When the pressure reaches $5\sim6\times10^{-5}$ Torr, the magnet cooling begins. The valve V_1 is closed off in two hours after the beginning of the cooling down. If V_1 remains open until the cold bore temperature falls to a temperature lower than 10 K. He molecules backstreaming from the roughing system can be adsorbed onto the cold surface. Therefore, the valve V_1 must be closed off before the completion of cooling down.

In four hours, cold bore temperature reaches the liquid helium temperature, and the He accumulation continues while many kinds of magnetic measurements, including a quenching test, are carried out.

Prior to warming up the magnet, the valve $V_.$ and V_2 are opened and closed, respectively, and the situation shown in Fig. 1 is achieved. While the magnet is warmed up gradually, the accumulated helium desorbes from the cold bore surface. The variations of helium partial pressure and of the total pressure are monitored up to 20K by the mass analyzer and the B-A gauge, for checking a status in the measurement system. At 20K, accumulated He on the cold bore is completely desorbed.

According to the formula (11), He partial pressure P_{MA} measured at $20^{o}K$ gives the He accumulation rate M.

$$M = \frac{P_{MA}\ S_{MA-BA}\ S_{N_2-He}}{} \frac{1}{mA} \sqrt{\frac{1}{T_r T_b}}\ \frac{Vb}{k}\ (365 \times 24) \tag{11}$$

Putting the constants in Table 1 into (11) leads to

$$M = 4.85 \times 10^{6}\ \frac{P_{MA}\ S_{MA-BA}}{t_{hr}\sqrt{T_b}} \quad \text{(monolayers/year)} \tag{12}$$

where

(P_{MA}: Reading on mass analyzer in Torr

(t_{hr}: Total accumulation period in hours

(T_b: Temperature of the cold bore at the PMA measurement

(S_{N_2-He}: Relative sensitivity of He to N_2 measured by calibration procedure (see Appendix).

Details of the measurement procedure are described in an Appendix.

4. Typical Results

The typical traces in the helium partial pressure measurement are shown in Fig. 3. Traces of A, B and C stand for the output voltage from the mass analyzer, B-A gauge and carbon resistor respectively. The zero points are taken at a common level and indicated by an arrow.

The carbon resistor used in this measurement has a value of 100Ω at room temperature and the calibration curve is shown in Fig. 4 at a current of 10μA. The output voltage of 8.3m$\bar{V}$ shown in Fig. 3, corresponds to 4.6K. The output voltage decreases quickly after the beginning of the warming up procedure. Since the resistivity of the carbon resistor is very sensitive to the temperature below 8K, the actual temperature variation is not so steep as the output voltage of the carbon resistor shown in Fig. 4. The details of the warming up procedure are shown in Table III.

As seen from the output of the B-A, the total pressure throughout the measurement is on the order of 10^{-7}Torr and remains low enough for the He partial pressure measurement.

The trace A for the He partial pressure is recorded with the mass analyzer range at 10^{-10}. As seen from the trace A, the He desorption begins at 9K and the trace A forms a small peak around 10K. This peak is considered to come from a variation of the surface condition inside the cold bore. There may be a corresponding change of adsorption energy onto the surface at this temperature.

A fine adjustment of the mass number dial on the mass analyzer was made around this small peak to obtain the exact reading of He partial pressure.

There is a rapid increase of the He partial pressure at 16K. Almost all of the accumulated He molecules are considered to desorb at this temperature. Above 17K, up to 20K, the He partial pressure increases with a rate, and this temperature region is suitable for the measure for the He accumulation rate.

The He partial pressure P_{MA}, obtained in this measurement, is 4.0×10^{-9} Torr at 20K. By the use of this P_{MA} and t_{hr}, shown in Fig. 3, eq. (12) gives the He accumulation rate of 1.03×10^{-4} monolayers/year.

APPENDIX

Measurement Procedure

The measurement procedure is divided into two parts (A) and (B). The former is for normal measurement and the latter for a calibration of the mass analyzer. This calibration should be carried out after replacing the mass analyzer head or B-A gauge head and their filaments, and also after tuning of the electronics for the mass analyzer.

(A) Measurement

I. Vacuum leak test of the system.

This leak test should be performed after an installation of a magnet. Prior to the test, make sure that there is no superinsulation around the warm bore tube.

1) Make sure that the thermo couple gauge is on and the B-A gauge is off.
2) Turn off the turbo molecular pump.
3) Close the valve V_3 on the rotary pump.
4) Make sure the rotary pump is on.
5) Connect a helium leak detector to the quick coupler flange downstream of the valve V_4 then open the valve V_4.
6) Open the valve V_3.
7) If the pressure is less than 0.1 Torr, turn on the turbo-molecular pump, otherwise, continue the leak test with turbo-molecular pump off.
8) Perform a leak test by the use of the He-leak detector. There may be a vacuum leak at the C-seal flanges. If there is a leak, fix it by tightening the bolts of the flange or changing the C-seal gasket to a new one.

9) Close the valve V_4 on the rotary pump.

10) Disconnect the helium leak detector.

II. Preliminary pumping down at room temperature

1) Make sure that the mass analyzer and the B-A gauge are off.

2) Make sure that the chart recorder is set as follows:
channel 1 : B-A gauge output with 1V full scale
channel 2 : Mass analyzer output with 10V full scale
channel 3 : Carbon register voltage with 10 mV full scale

3) Turn on the carbon register current supply and the multimeter. Make sure the reading on the multimeter is around 0.98mV.

4) Write down the operator's name, date, and time on the chart.

5) Turn on the chart recorder with a speed of 2cm/hour.

6) Open valves V_1 and V_2.

7) Turn on the rotary pump and the thermocouple gauge.

8) Wait until the pressure reading falls to 0.5 Torr. (It will take about 3 minutes.)

9) When the pressure reading is 0.5 Torr, turn on the turbo-molecular pump.

10) Make sure that the pressure goes down to 10^{-3} range within 3 minutes.

11) Wait 10 minutes.

12) Turn on the B-A gauge with the range selector at "AUTO" and turn on the filament. If the pressure reading is higher than 1×10^{-3}Torr, turn off the filament and wait 5 minutes. Repeat this procedure until obtaining the pressure reading below 1×10^{-3}Torr.

13) When the pressure reading of the B-A gauge reaches $5x10^{-5}$Torr, turn on the mass analyzer power. It will take about 2 to 3 hours to reach this pressure after turning on the turbo-molecular pump.

14) Wait 10 minutes.

15) Make sure that the scanning mode-selector of the mass analyzer is at "manual" position, range selector is at 10^{-5}, and the emission current selector is at "Calib" (1mA).

16) Turn on the filament of the mass analyzer.

17) Set the mass number dial according to the value in the previous measurement.

18) Adjust the zero points of the chart recorders.

channel 1 : Turn off the filament.

channel 2 : Range selector of the mass analyzer to zero.

channel 3 : Short the input terminal.

III. Cooling down

1) Start the magnet cooling down.

2) Close the valve V_2 in 2 hours from the beginning of cooling down.

3) When the magnet temperature reaches liquid helium temperature, the normal magnet measurements are carried out.

IV. Helium partial pressure measurement.

1) Set the range selector of the mass analyzer at 10^{-10}.

2) Check the status of the system according to Table V.

3) Check the zero points of the chart recorder.

4) Write down the present ranges for each channel and date and time.

5) Open valve V_1 and close valve V_2.

6) Set the chart recorder speed to 10mm/min.

7) Start the warming up according to the procedure shown in Table III.

This warming up must be carried out slowly and the complete warming up to 20K takes 20 minutes or more.

8) When the voltage reading of the carbon register reaches 3.5mV ($\sim$9K), adjust the mass number dial to give the maximum helium peak height and write down the mass number on the dial at the maximum.

9) If the output of the mass analyzer exceeds the full scale of the recorder, change the range of the mass analyzer and write down the new range on the chart.

10) If the pressure reading of the B-A gauge becomes higher than the value 4×10^{-5}Torr before the temperature reading reach 20K. Shut off the mass analyzer and B-A gauge. This is an abort run. Go ahead to step 12.

11) When the voltage reading of the temperature reaches 1.8mV (above 20K) the measurement is ended.

12) Open valve V_2 and turn off the mass analyzer and the B-A gauge.

13) When the cold bore temperature reaches room temperature, turn off all electronics.

14) Turn off the turbo-molecular pump and close the valve V_3.

15) Wait 3 minutes and open the leak valve V_5 slowly.

(B) Calibration of the Mass-Analyzer.

The pressure of the system must be lower than 3×10^{-7}Torr for this calibration.

1) Connect the He bottle to the vacuum system. (See Fig. 6.)

2) Make sure the variable leak valve is closed.

3) Close the valve of He bottle and turn on the rotary pump.

4) Pump out the air inside of the piping between He bottle and the variable leak valve.

5) Close the valve V_6.

6) Open the valve of He bottle and set the regulator slightly higher than 1-atmospheric pressure.

7) Set the chart recorder as indicated in App-A, II-2) and chart speed to 5 cm/min.

8) Write down the B-A gauge pressure, this is called base pressure.

9) Open the variable leak valve slowly and increase the pressure up to 0-5 times higher than the base pressure.

10) Adjust the mass number dial to the He-peak.

11) Keep the pressure for 2 min.

12) Increase the pressure $\sim$2 times higher than the previous value and keep it for 2 min. Write down the pressure range of B-A gauge and mass analyzer.

13) Repeat step 12) until the pressure reaches to 2 x 10^{-5}Torr.

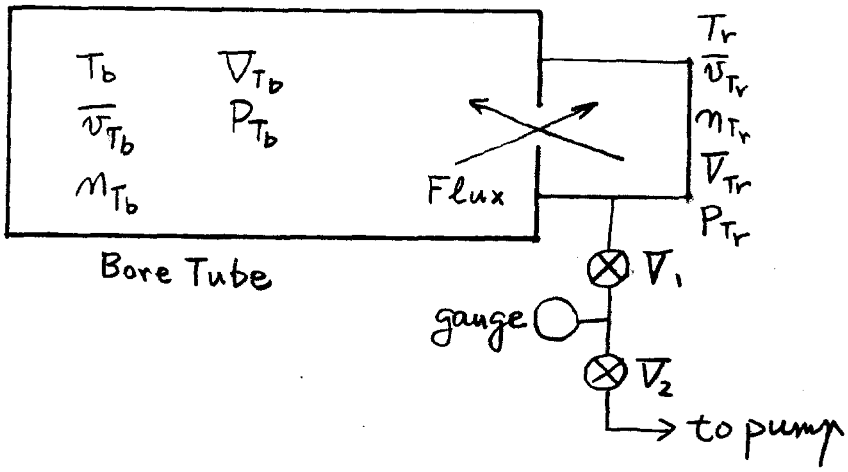
14) Scan the mass analyzer and make sure the He peak is the only one on the chart.

15) Close the variable leak valve.

16) Close the valve of the He bottle.

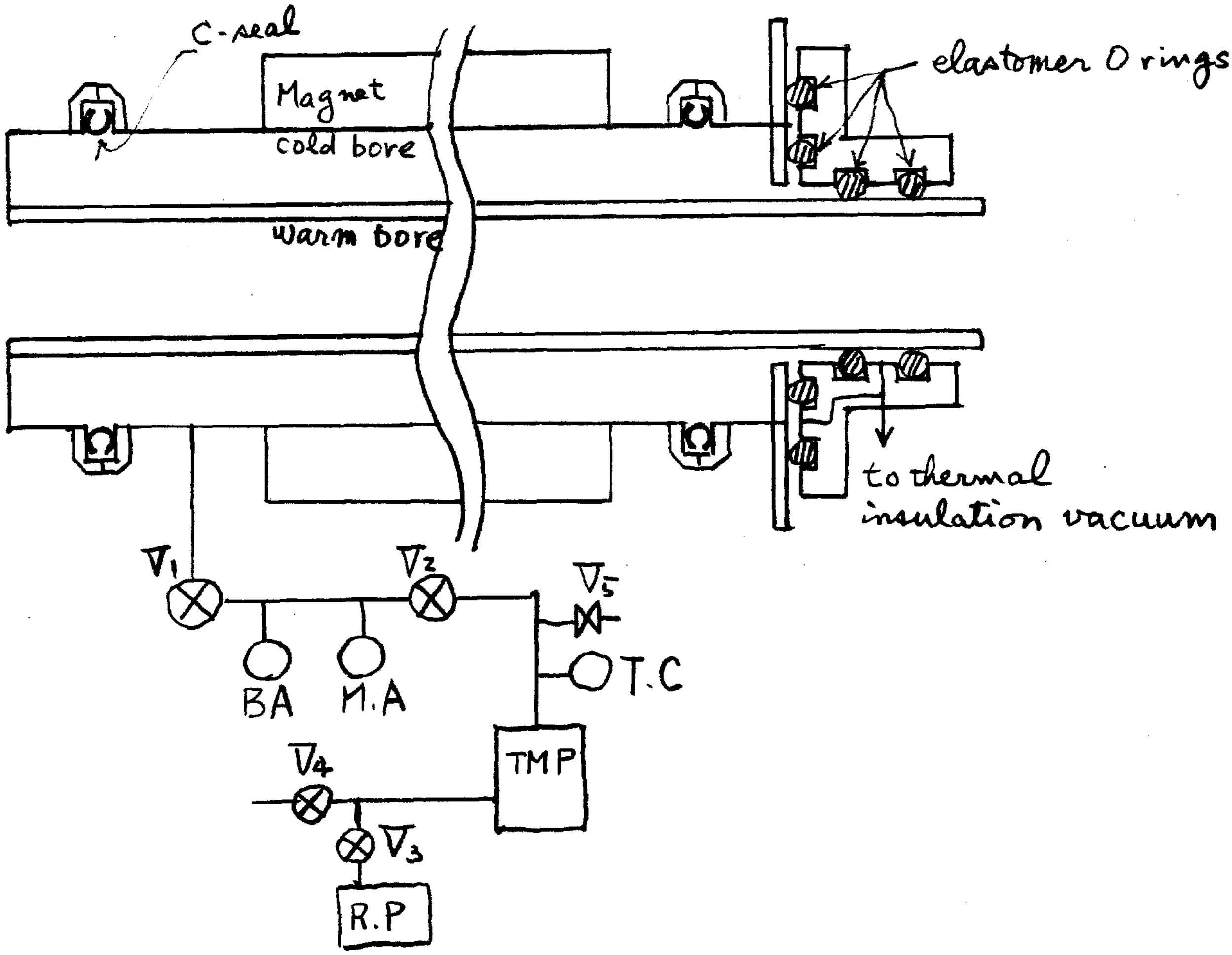
17) Stop the rotary pump.

Fig - 1



T_b
$\bar{v}_{T_b}$
n_{T_b}
V_{T_b}
P_{T_b}
Flux
Bore Tube
T_r
$\bar{v}_{T_r}$
n_{T_r}
V_{T_r}
P_{T_r}
V_1
gauge
V_2
to pump

Fig 2



C-seal
Magnet
cold bore
warm bore
elastomer O rings
to thermal insulation vacuum
V_1
V_2
V_5
T.C
BA
M.A
TMP
V_4
V_3
R.P

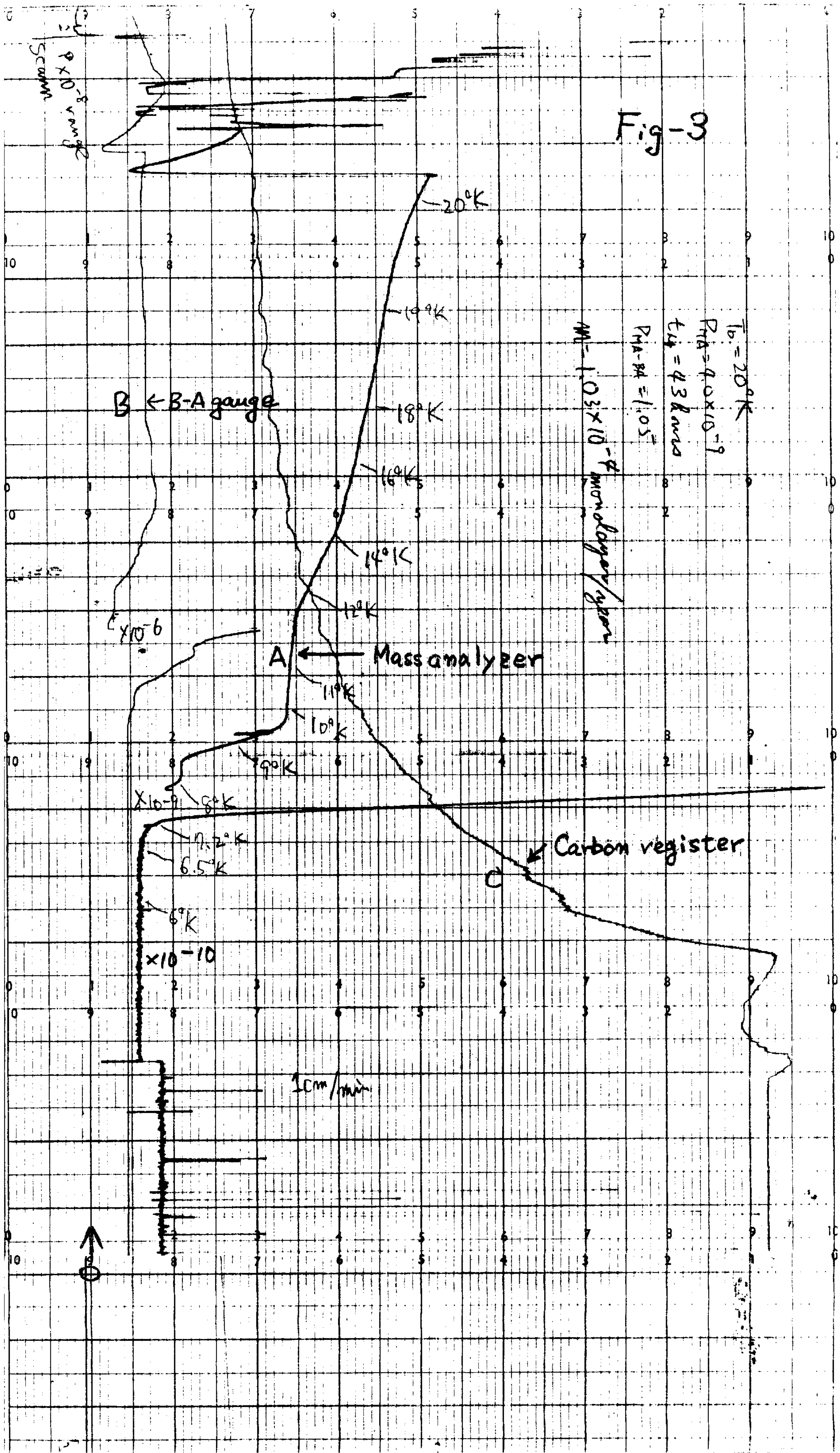


Fig-3
20°K
19°K
B ← B-A gauge
18°K
16°K
14°K
12°K
×10-6
A ← Mass analyzer
11°K
10°K
9°K
×10-9
8°K
7.2°K
6.5°K
Carbon register
C
6°K
×10-10
1cm/min

Fig-4

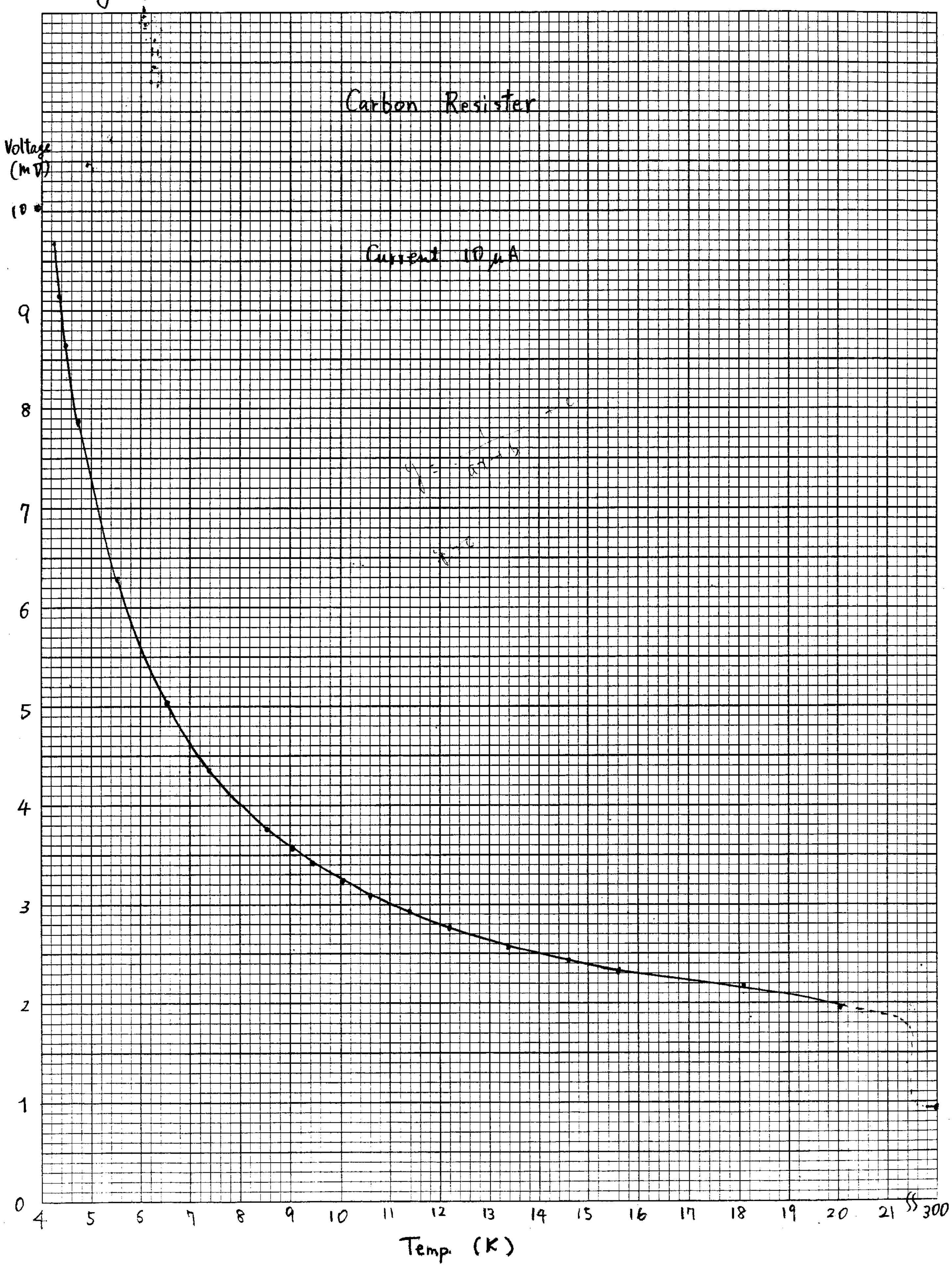

Carbon Resister
Current 10 μA
Voltage (mV)
10
9
8
7
6
5
4
3
2
1
0
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
300
Temp. (K)

Fig-5-a

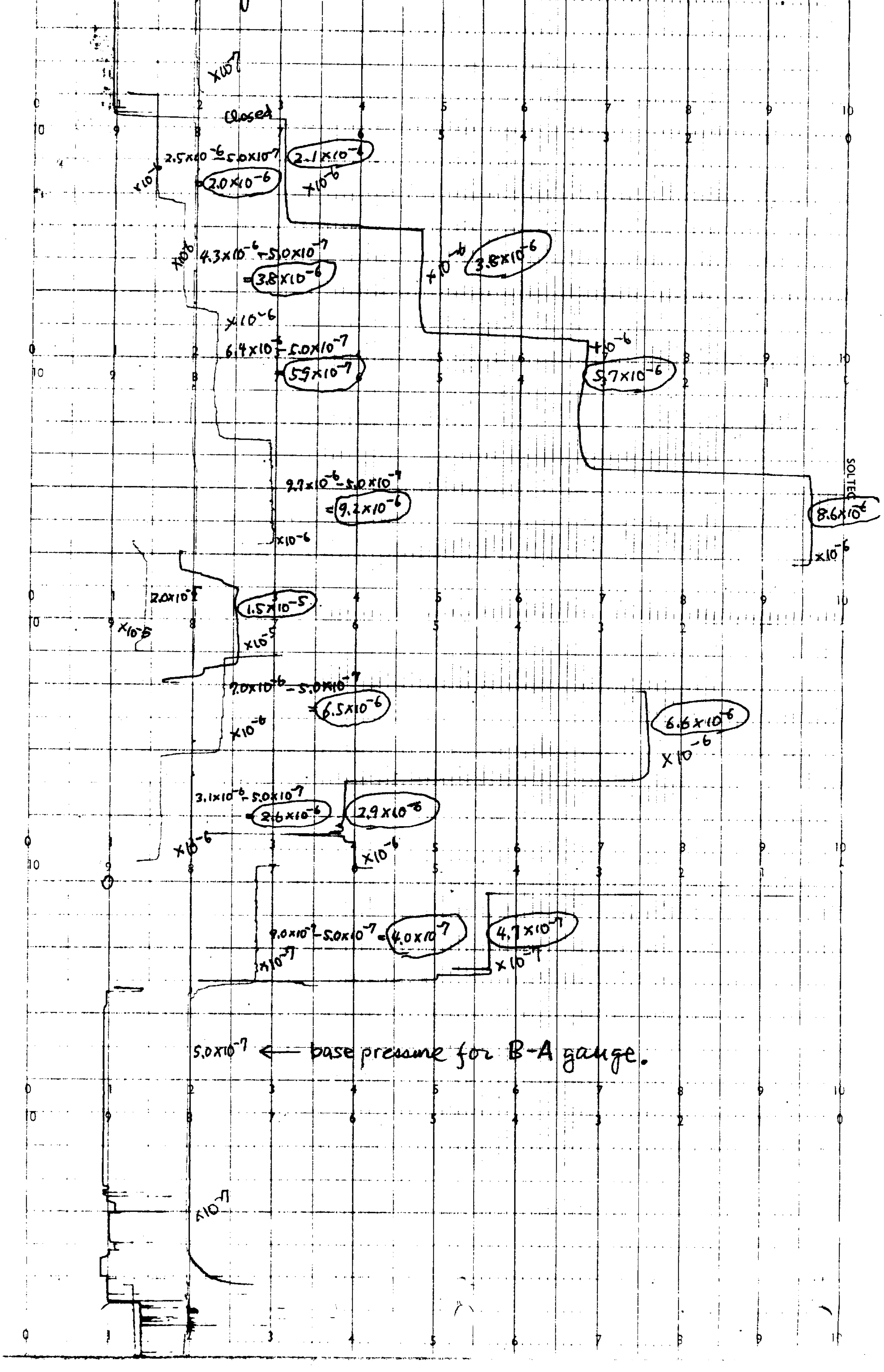
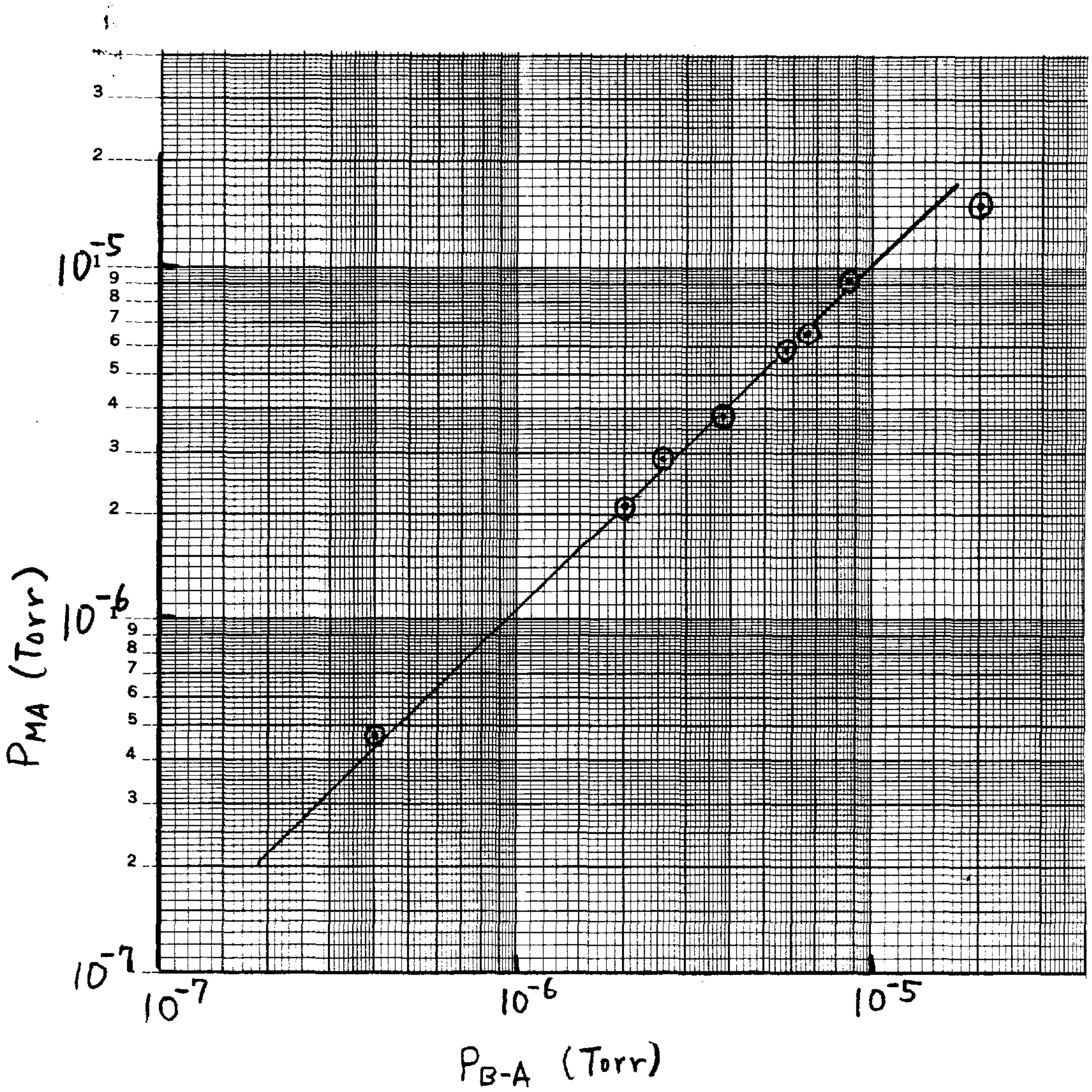

x10^-7
Closed
2.5x10^-6 - 5.0x10^-7
= 2.0x10^-6
x10^-6
2.1x10^-6
x10^-6
4.3x10^-6 - 5.0x10^-7
= 3.8x10^-6
x10^-6
3.8x10^-6
x10^-6
x10^-6
6.4x10^-6 - 5.0x10^-7
= 5.9x10^-7
x10^-6
5.7x10^-6
9.7x10^-6 - 5.0x10^-7
= 9.2x10^-6
x10^-6
8.6x10^-6
x10^-6
2.0x10^-5
x10^-5
1.5x10^-5
x10^-5
7.0x10^-6 - 5.0x10^-7
= 6.5x10^-6
x10^-6
6.6x10^-6
x10^-6
3.1x10^-6 - 5.0x10^-7
= 2.6x10^-6
2.9x10^-6
x10^-6
x10^-6
9.0x10^-7 - 5.0x10^-7 = 4.0x10^-7
x10^-7
4.7x10^-7
x10^-7
5.0x10^-7 ← base pressure for B-A gauge.
x10^-7
SOLTEC

Fig 5-b



$S_{MA-BA} = 1.05$

Fig-6 Set-up for calibration

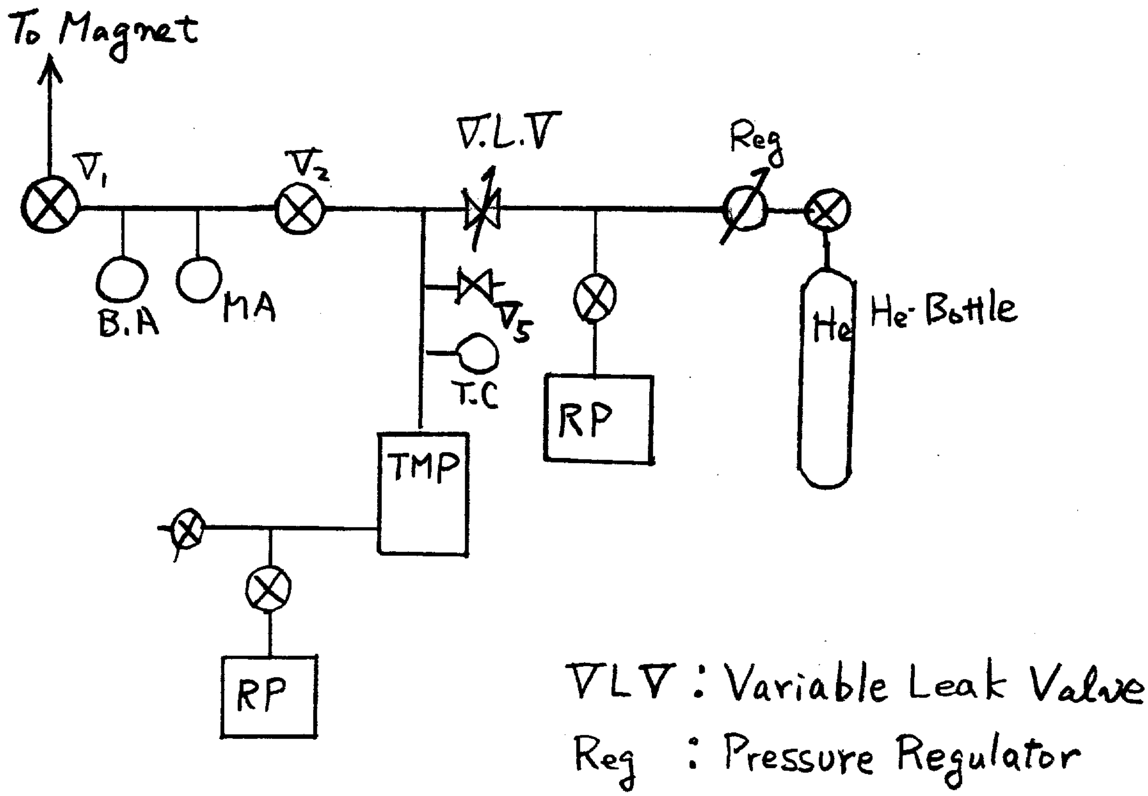


Table I-Notation

T_b	:	Cold bore temperature
T_r	:	Room temperature
N_{Tb}	:	Helium molecular density in the cold bore tube.
N_{Tr}	:	Helium molecular density in the measurement port.
V_{Tb}	;	Mean velocity of the helium molecule at the temperature T_b
V_{Tr}	:	Mean velocity of the helium molecule at the temperature T_r
P_{Tb}	:	Pressure in the cold bore tube at the temperature T_b
P_{Tr}	:	Pressure in the measurement port at the temperature T_r.
P_{MA}	:	Helium partial pressure measured by a mass analyzer.
m_{He}	:	Mass of helium molecule.
k	:	Boltzmann constant: 1.38×10^{-16} erg K^{-1}.
m	:	Number of helium molecules of 1-monolayer per unit area. (2.6×10^{15} moles/cm^2 on stainless steel surface: See P381 Table 6-3 "Scientific Foundation of Vacuum Technique": Dushman & Laflerty: Wiley)
V	:	Volume of the cold tube: 7.0×10^3 cm^3.
A	:	Surface area of the cold bore: 1.3×10^4 cm^2
t_{hr}	:	Cooling period of time in hours
M	:	Helium accumulation ratio in monolayers/year.

Table II

V_1	:	closed
V_2	:	open
Turbo molecular pump	:	ON
B-A gauge	:	ON, Auto-range mode, Ie = 0.4 mA
Mass analyzer	:	ON, Filament ON Ie = 1mA
Chart recorder	:	channel I 1V full scale
		channel II 10V full scale
		channel III 10mV full scale
		chart speed : 1 cm/hour
Carbon resistor	:	10μA power supply : ON
Multimeter	:	ON DCV 200 mV

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Table III

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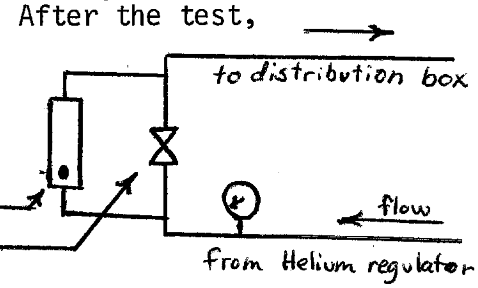
SUBJECT: Warm-up Procedure for Vacuum Test on TS#4

All steps must be followed as quickly as possible in sequence. If done correctly, warm-up should take about 20 minutes. The entire length of the warm bore must reach 20°K or warmer. Naturally, the magnet will get quite a bit warmer than this (up to 175°K) where the gas comes in. After the test, the magnet may be warmed in the normal way or recooled.



Set-up

1. Make sure no stands are warming or scrubbing.
2. Make sure valve on flowmeter is closed.
3. Close this ball valve.
4. Set JT regulator pressure to 25 psi.
5. Set green valve cursor on JT Fischer controller (PV-548-4) for TS #4 to 30%.

Warm-Up

1. Close PV-431-4 with Fischer controller TIC-499-4.
2. Close MV-432-4.
3. Open 2" ball valve to suction.
4. Open the two upstream end bypasses (MV-567-4 and MV-568-4).
5. Open PV-462-4 and MV-463-4.
6. Open valve on Helium warm-up gas flowmeter and set flow at 50 scfh.
7. When pressure surge in the magnet (due to warm gas meeting the liquid) subsides, i.e. when magnet pressure is about 3 psi., open JT to 100%. This may increase flow through the Helium warm-up gas flowmeter up to 100 scfh - this is OK- do not re-adjust to 50 scfh.